

DEVELOPMENT OF A LOW-COST MEASUREMENT SYSTEM FOR CUTTING EDGE PROFILE DETECTION

Gregor Gerstorfer, Bernhard G. Zagar

Institute for Measurement Technology, Johannes Kepler University, Altenbergerstraße 69, 4040 Linz, Austria
E-mail: gregor.gerstorfer@jku.at, bernhard.zagar@jku.at

Abstract — This paper describes the use of a CD pickup head as a displacement measurement system. First, the components contained in a pickup head are explained and how they are combined to obtain the functionality of a pickup head. Afterwards, the application of measuring a knife edge profile is introduced. The results revealed some insufficiencies with the current system. Nevertheless, the cutting edge's radius of curvature can be estimated.

Keywords — optical pickup head, CD, profile measurement.

I. INTRODUCTION

When knives are produced, a main point of interest is their sharpness of the cutting edge. A way to measure the radius of curvature of the cutting edge is to use commercially available optical pickup heads of standard CD drives and let them scan the distance to the knife's surface.

Several different applications using an optical pickup head as a measurement system can be found in [1], [2] or [3]. As [4] mentioned in his work, most of those applications are relying on assumed ideal reflective properties of the surface of the specimen.

In former publications an approach to scan a knife edge using a pickup head can be found [5]. In contrast to our work, where only a CD pickup head is required, an interferometer setup and a redirecting mirror are necessary, too.

Preliminary to the use of a CD pickup head as a sensor system, several investigations have to be carried out. These investigations ought to deliver information about the electrical and mechanical structures and characteristics of those high quality but still low cost pickup heads. Main focus is given to the so called focus error signal, conveying the sought after measurement infor-

mation of a change in distance to the reflective probe surface.

With an optical pickup head as a profile measurement system, there are two different operating modes: In the first mode, the specimen is placed in the focal plane and the objective lens is kept fixed. The focus error signal can then directly be calculated into the surface roughness of an object moving laterally to the sensor. Alternatively in the second mode, the objective lens' position is servoed to keep the focus error signal close to zero giving the advantage that the system is always operating in focus. The drive current or voltage respectively of the objective's actuator is then a direct though slightly non-linear indicator for the profile of the object moving along the sensor, as long as the linear range of the focus error signal is not dynamically overwhelmed. The useful working range in this mode is more than 100 times the range of the first mode and amounts to approximately 1mm of displacement.

In this work, we will focus on the first mode, which is actually used for detecting the profile of a cutting edge.

The paper is organized as follows: first the optical setup is introduced and its functionality as well as the signals delivered by the pickup head are explained. Subsequently, the voice coil motors' characteristic are investigated. In the next part, the use of a pickup head as a measurement system is illustrated, followed by a measurement example and derived result.

II. THE CD PICKUP HEAD

Optical storage systems usually consist of a rotating data storage medium, an optical pickup head for reading the information and electronics for controlling the mechano-optical system and for converting the gained data. In this project a CD pickup head (Mitsumi PXR-550X) from a commercially available CD-drive for profile measurement was investigated.

A. The Functionality of a Pickup Head

Figure 1 shows the principle of a CD pickup head. It

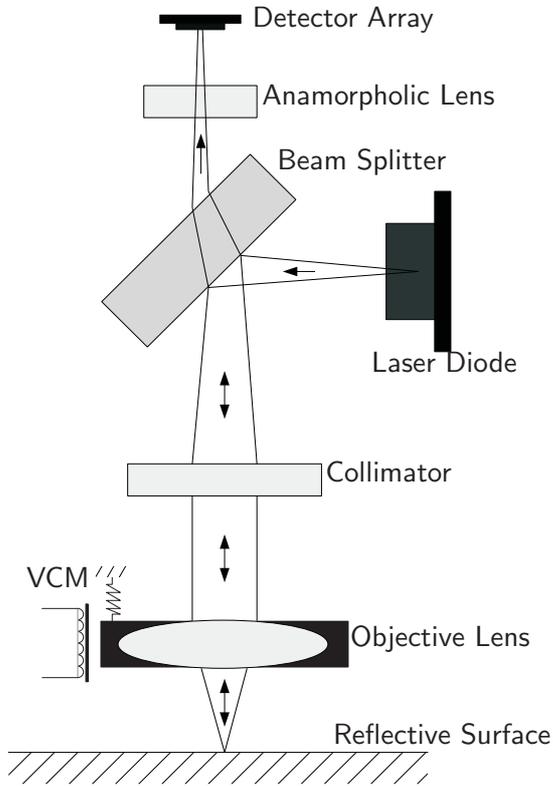


Fig. 1: The principle of a CD pickup head (beams shown for the focused case).

consists of a laser diode operating at a wavelength of 780 nm, a linearly polarizing beam splitter, a collimator, an objective lens, an anamorpholic lens in front of the detector array and some more parts, which don't show an importance to the working principle. Subsequently, the laser beam is polarized and collimated, it is directed via the objective lens to the specimen. The objective lens is actuated by the voice coil motors, their characteristics will be discussed in the next section. The specimen scatters back the beam through the objective lens to the beam splitter, where it is directed via the anamorpholic lens onto the detector array. The detector array is a four-quadrant photo diode – the four photodiodes' arrangement is shown in Fig. 2 – with two additional photodiodes which are used for holding the track while scanning CDs (these additional photodiodes are not used in this work and not shown here). Because of the characteristics of the anamorpholic lens,

the beam shape at the detector array is either elliptic or circular. The circular shape occurs only if the reflective surface of the specimen is placed exactly at the focal plane of the optical path. The laser beam in this case has a diameter of less than $1 \mu\text{m}$. The elliptic shape occurs when the beam reflection takes place out of focus. The orientation and size of the elliptic beam pattern respectively depend on the location and distance from the focal plane. The detector array has, as already mentioned, four areas, named A, B, C and D. They deliver photocurrents, depending on the illuminance integrated over their area, which are subsequently linearly converted into voltages. From these voltages the so-called focus error (FE) signal can be derived:

$$FE = (A + C) - (B + D). \quad (1)$$

The FE signal has an s-shape when a reflecting object is in certain range of the focal plane. The relations between the FE signal and the specimen's travel distance are shown in Fig. 2. The FE signal in this figure

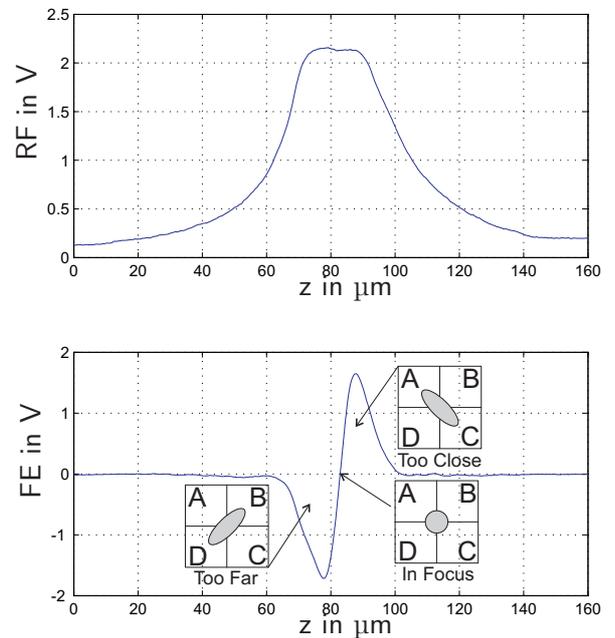


Fig. 2: Bottom: The FE signal's characteristic s-curve with corresponding beam shapes at the detector array. Top: The RF signal associated with the FE signal.

has been obtained by keeping the objective lens at a

fixed position and then moving a mirror like specimen towards the pickup head. The mirror's velocity was approximately $v_z = 10 \mu\text{m/s}$. The s-curve is approximately linear over an input range of $6 \mu\text{m}$.

Beside the FE signal also the total illumination integrated over all four photodiodes, called RF signal, is of interest:

$$RF = A + B + C + D. \quad (2)$$

The RF signal is plotted together with the FE signal in Fig. 2.

B. The Voice Coil Motors

To move the objective lens in a 2D-space or to keep it at a certain position, there are two voice coil motors (VCM) available, included in the pickup head and they are able to move the objective lens orthogonally and radially to the CD-surface. To investigate the static behaviour of the two voice coil motors, excitation voltages are applied and the relation between the applied voltage and the travel distance is measured. A laser vibrometer (Polytec OFV-505) has been used to obtain the travelled displacement. As Fig. 3 shows, the VCM in focus direction features a linear excitation range of $u_o = \pm 0.5V$, corresponding to a travelled distance of $z = \pm 0.54 \cdot 10^{-3} \text{ m}$. These two values yield to a sensitivity of the VCM in focus direction over the nominal range of

$$\frac{z}{u_o} = 1.1 \frac{\text{mm}}{\text{V}}. \quad (3)$$

The linear excitation range of the VCM in radial direction also ends at $u_r = \pm 0.5V$ but it exhibits less sensitivity:

$$\frac{x}{u_r} = 0.8 \frac{\text{mm}}{\text{V}}. \quad (4)$$

The dynamics of each VCM is determined by measuring its Bode-plot with amplitudes limited to the linear range of input voltages. The resolved magnitude responses for both, the radial and the orthogonal VCM respectively, are displayed in Fig. 4. The resonance frequencies for both directions are found to be slightly above 50 Hz.

From Fig. 4 one can infer that the VCMs together with the objective lens can be modelled as a forced

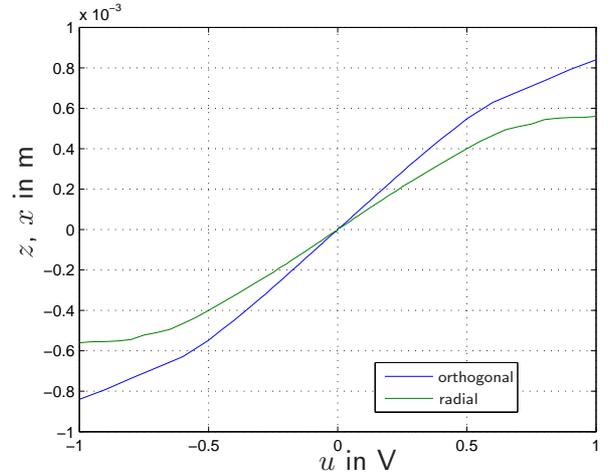


Fig. 3: The relation between VCM movement and supplied voltage. Both VCM show a linear range between $\pm 0.5V$ for a travel of $\pm 0.54 \text{ mm}$ in orthogonal direction and $\pm 0.4 \text{ mm}$ in radial direction, respectively.

second order system:

$$m \cdot \ddot{x}(t) + d \cdot \dot{x}(t) + c \cdot x(t) = f(t), \quad (5)$$

where m represents the accumulated mass of the moving parts (windings of the VCMs, objective lens and lens holder) and d and c mark the damping coefficient and the spring stiffness of the system, respectively. Figure 5 pictures a mechanical model of a VCM/lens system. The wires connecting the VCMs act as springs and have equal stiffnesses in each moving direction. The damping coefficient is derived from the magnitude response of very small amount. The weight of the moving parts amounts to $m = 385 \cdot 10^{-6} \text{ kg}$. The spring stiffness was identified and amounts to $c = 27.06 \text{ N/m}$ (see below). Finally, the damping coefficient is estimated to $d = 0.01 \text{ Ns/m}$. Using Laplace transformation the equation of motion can be expressed as a transfer function

$$G_{x/f} = \frac{X(s)}{F(s)} = \frac{1}{m \cdot s^2 + d \cdot s + c}. \quad (6)$$

Actually, a transfer function $G_{x/u}$ is of interest which describes the objective lens' travel $x(t)$ on an excitation voltage $u(t)$:

$$G_{x/u} = \frac{X(s)}{U(s)} = \frac{k}{m \cdot s^2 + d \cdot s + c}. \quad (7)$$

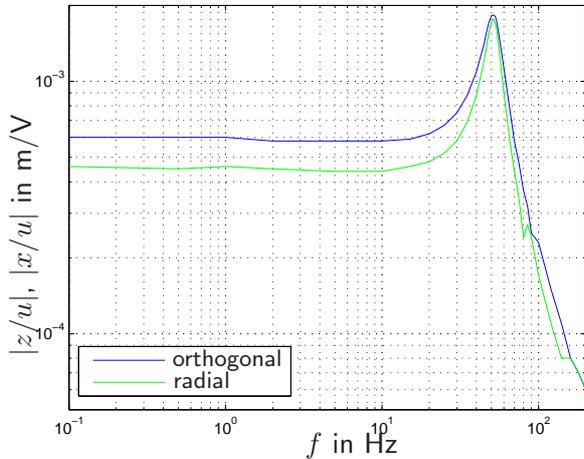


Fig. 4: VCM's magnitude response of the bode-diagram for a peak excitation voltage of $U_{o,r} = 0.1$ V.

Here, the motor factor k specifies the f/u characteristic of the VCM in the linear range. Due to the electric systems having time constants much shorter than those of the mechanical systems, it suffices to use the factor k . A simple test is used for determining this factor: determine the lens displacement at a certain excitation voltage and repeat the test with an extra mass applied to the moved parts. This test lets us compute the spring stiffness c and the motor factor k , which amounts to $k = 49.104 \cdot 10^{-3}$ N/V. Figure 6 depicts the resulting Bode-diagram of the transfer function $G_{x/u}$.

In comparison to the measured system from Fig. 4, the resonance frequency can be found at a lower frequency of $f = 42$ Hz. The gain at frequencies $f < 10$ Hz originally amounts to $|z/u| = 0.6 \cdot 10^{-3}$ m/V but is now $|z/u| = 1.82 \cdot 10^{-3}$ m/V. These errors occurring with the identified model have to be investigated before the VCMs are controlled to servo the focal plane and the laser beam position, respectively. A possible source of error is the test setup which is used to identify the factors k and c . This setup has to be improved by using a laser vibrometer instead of now calculating the displacement relations obtained by macro photography.

The detailed investigation of the dynamic characteristics of the VCM is used for future work, where the VCM moves the objective lens in horizontal direction to scan across a knife edge. Hence the VCMs then have to be controlled, an exact equation of motion is necessary.

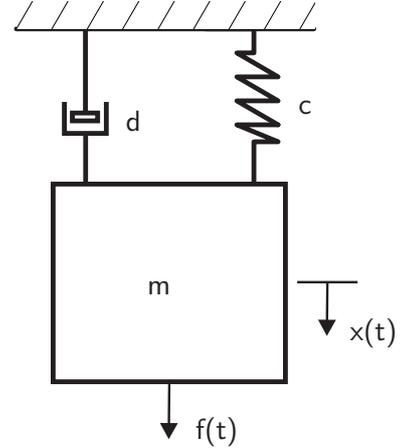


Fig. 5: A forced second order system modelling a pickup head's mechanical system containing the moving parts (objective lens, the lens holder and the windings of the VCMs), a spring and a damping.

Ensuing the information about the pickup head's electrical and mechanical characteristics, the following sections describe two different ways of using such a pickup head as a profile measurement system.

III. THE PICKUP HEAD AS A PROFILE MEASUREMENT SYSTEM

Two different modes of using the pickup head as a profile measurement system can be distinguished. In the first mode the specimen is positioned at the focal plane. Meanwhile, the objective lens is fixed at its rest position. Subsequently, the pickup scans across the surface and the obtained FE signal gives information about the surface roughness. The resolution in this mode amounts to $\pm 3 \mu\text{m}$ as has already been explained with Fig. 2. The second mode is characterized by the control of the vertical objective lens' position, so that the FE signal is servoed to zero. In this mode there is a larger range that can be utilized, accompanied by a lower resolution, however. For this reason, the first mode is the chosen one to detect the profile of a knife's cutting edge.

A. Cutting Edge's Profile Detection

As a test specimen a standard blade of a Stanley knife is used. It is clamped tightly to a 2D motion controlled

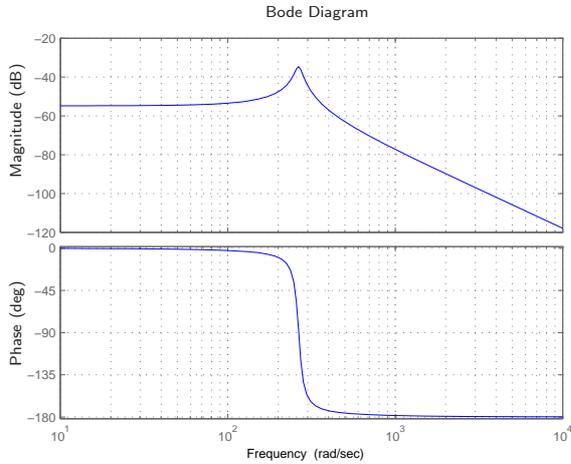


Fig. 6: Bode-diagram of the identified system $G_{x/u}$. The resonance frequency is at 42 Hz, the gain amounts to $1.82 \cdot 10^{-3}$ m/V for frequencies $f < 10$ Hz.

micro translation stage (Oriol Encoder Mike) and can be moved orthogonally and radially. The pickup head as well as the motion control with the clamped knife are all assembled to an active vibration absorber (Halcyonics Micro 40) so that the measurement system is somewhat less affected by external mechanical disturbances. After the knife edge is placed into the focal plane, the motion control moves the knife edge horizontally along the pickup head. The output voltages A to D are acquired with a digital storage oscilloscope (Tektronix TDS 2024), the data is sent to (via GPIB) and evaluated on a computer.

The FE signal which is expected when a circularly rounded tip of a knife edge is scanned, is shown in Fig. 7. The RF signal will strongly decrease when the laser beam leaves the focal plane, because the beam is no longer properly reflected in the orthogonal direction. This fact prohibits the FE signal's transformation into an exact information of the knife's edge profile. But the broadness of the knife edge in the focal plane can be estimated, which still gives information about the quality.

In Fig. 8 the measured RF and FE signals are shown. In this figure, the red area marks the estimated broadness of the knife edge, beginning at the minimum of the FE signal. For finding the estimated area's end, one has to act another assumption: when the RF signal falls below a certain limit (at $RF = 0.4$ V) while the

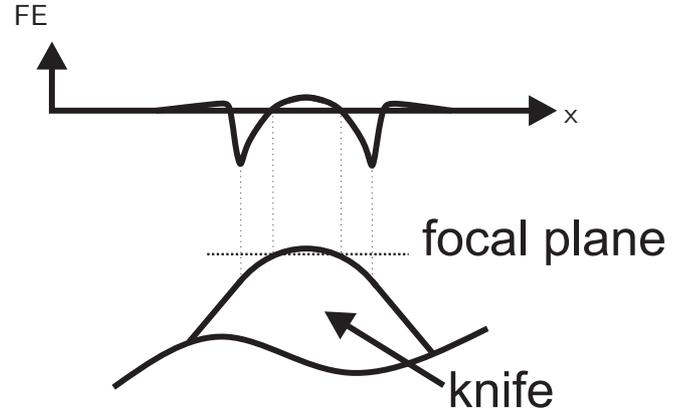


Fig. 7: The expected FE signal when scanning the knife's edge. The leftmost vertical dashed line marks the begin of the FE signal's linear range. The reflection on the detector array appears as an elliptic shape. The two vertical lines in the middle mark the points where the reflection takes place in the focal plane. In between these two lines, the scanned surface is in the positive defocus to the lens, so the FE signal becomes positive. The rightmost line marks the end of the scanable surface because the FE signal leaves its linear range.

FE signal is still not yet zero, one can assume that the laser beam's main part is reflected into another direction. This implies the beam has already left the circular part of the profile. With these assumptions, one can estimate the width of the knife edge to be $12 \cdot 10^{-6}$ m, according to the measurement from Fig. 8.

One of the main problems appearing while measuring is the uncertainty about the exact profile shape. Due to the bevel of the knife at its edge, the laser beam is no longer reflected into the middle of the detector array but rather onto one side of the array. These facts lead to measurement results which can only be interpreted but not transformed into an exact profile. Another problem appears in the slightly improper alignment of the laser-beam and the knife. In Fig.9 another source of error can be seen: the picture of the detector array with the four areas A, B, C and D can be spotted and it strikes out, that there is a slight deviation in angle of about 6° . This deviation has to be investigated in future work like each of the other mentioned uncertainties.

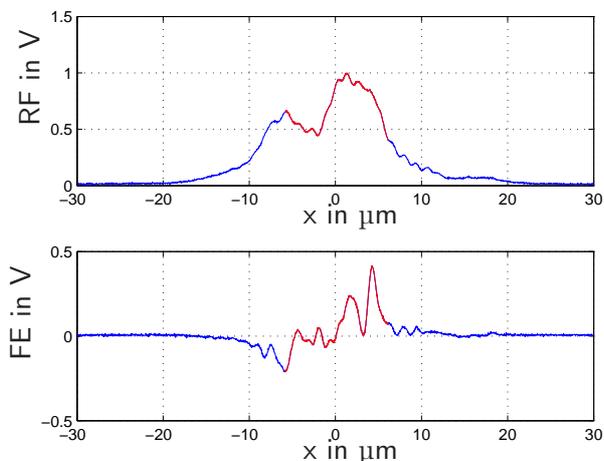


Fig. 8: Measured RF and FE signal while scanning a knife edge. The red area marks the estimated broadness of the knife edge.

IV. CONCLUSION

This paper has shown the adaptability of a CD pickup head as a measurement system for characterizing a knife's edge profile. The optical and mechanical characteristics of such a pickup head has been shown. For pickup heads, there are two different ways to use them for profile detection. Firstly by controlling the objective lens and keeping the focus error to zero, and secondly by placing the object at the focal plane and then scanning across the object. This second option has been used for the work described in this paper. The experienced uncertainties prohibit an exact conclusion about the measured edge profile.

Future work will mainly focus on developing several strategies to avoid the mentioned uncertainties and errors so that the measurement results provide information about the scanned edge profile. Subsequently these investigations will focus on using the VCMs instead of the micro stages. Thus the laser beam will travel across the specimen, instead of letting the specimen travel in front of the pickup head.

V. REFERENCES

[1] Kuang-Chao Fan, Chih-Liang Chu, Jong-I Mou, Development of a low-cost autofocus probe for

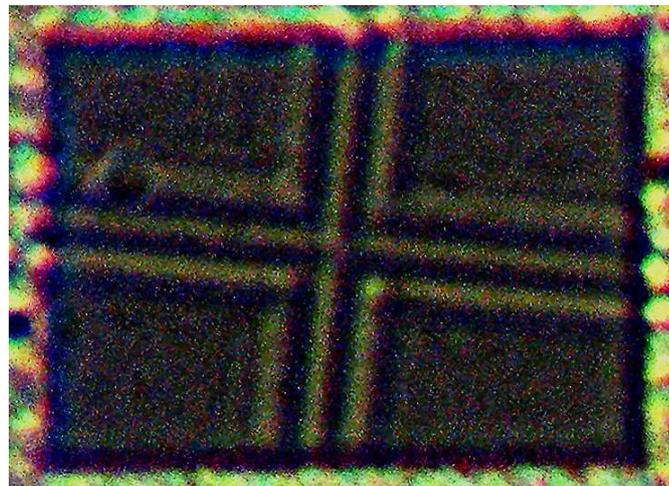


Fig. 9: Picture of the detector array ($b = 120 \mu\text{m}$, $h = 75 \mu\text{m}$), taken via a microscope. The deviation in angle of the four areas A to D can be identified. Artefacts (increased noise) appear due to sharpening filters.

profile measurement, Measurement Science and Technology, (12) 2001

- [2] En-Te Hwu, Kuang-Yuh Huang, Shao-Kang Hung, Ing-Shou Hwang, Measurement of Cantilever Displacement Using a Compact Disk/Digital Versatile Disk Pickup Head, Japanese Journal of Applied Physics, 45 (2006)
- [3] Stefan Kostner, Michael J. Vellekoop, DVD pickup heads for optical measurement applications, Elektrotechnik und Informationstechnik (e&i), 125 (2008)
- [4] Nashtara Islam, Robert Parkin, Peter Mueller, A Novel Surface Profile Measurement System, 10th International Conference on Mechatronics Technology (ICMT2006), 20-24 November 2006 Mexico City
- [5] Kuang-Chao Fan, Chih-Liang Chu, Jarn-Lien Mou, Jong-I Mou, Development of a high-precision straightness measurement system with DVD pickup head, Measurement Science and Technology, (14) 2002